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THE INFLUENCE OF DFIG ACCESS LOCATION ON THE TRANSIENT ANGLE STABILITY OF MULTI-MACHINE SYSTEM

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ABSTRACT

Large-scale wind farm has become an important factor affecting the transient stability of power system. In view of the lack of theoretical research on the transient power angle stability of multi-machine system connected with wind farm, this paper proposes a method to analyze the transient power angle stability of multi-machine system with doubly-fed induction generator (DFIG) based wind farm. By modifying and contracting the bus voltage matrix, thus the influence of wind farm on the mutual synchronization between synchronous generators is quantified to the variation of electrical distance between synchronous generators. Furtherly, according to the extended equal area criteria, the relation between the equivalent mechanical power of the system and wind farm's power output or access position is derived, and finally the influence regularity of wind farm access location on transient stability of practical multi-machine power system is revealed, which provides a theoretical guidance for the scientific configuration of wind farm considering the LVRT scheme and access location synthetically. In simulation, the variation of electrical distances between synchronous generator nodes caused by different DFIG location is analyzed, and the power angle variation in the cases of two LVRT schemes of DFIG at different grid connection point are simulated and compared to verify the validity of proposed method.

Keywords: wind farm, transient stability, multi-machine system, bus admittance matrix, low voltage ride through

1. INTRODUCTION

With the increasing demand for clean energy and as the wind power technology becomes advanced, wind power generation has been vigorously developed and applied around the world. The large-scale connection of wind farms has a great impact on the transient stability of the power system, which leads to the necessity to analyze the transient stability of the power system with wind farms.

Till now, many researchers use time domain simulation to study the transient stability of system with large-scale wind farms. In ref. [1], the effects of DFIG on the CCT (Critical Clean Time) at different locations are analyzed by replacing a synchronous generator with DFIG. Ref. [2] points out that while the fault occurs near the wind farm's PCC (Point of Common Coupling), the wind generators are detrimental to the transient stability. And while the fault is close to the synchronous generator, the wind farm is conducive to the stability system. To summarize, the time domain simulation method usually bases on the simulation results, at the same time, lacks theoretical support for those conclusions.

In recent years, there have been some studies in theory on the relevant issues. In ref. [3, 4], DFIG is regarded as active power injection source, and the transient stability of a double-machine system with DFIG is analyzed using simplified DC power flow model. However, during the low voltage ride through (LVRT) period, reactive power output by DFIG will affect the voltage and electromagnetic power of each generator. Ref. [5] draws the conclusion that LVRT schemes are beneficial to the transient stability of the synchronous generators near wind farm. However, not all LVRT schemes improve the terminal voltage of DFIG [6], and the impact of DFIG on remote synchronous generators is not concerned in ref. [5], so the conclusion is not prevailingly correct. Ref. [7], aims at studying multi-machine system, converts the synchronous generators' power angles to the center of inertia (COI) of a unified system to indicate the stability of the whole system with DFIG. However, this method cannot analyze the relative synchronization of the power angles of each two generators, and due to the simplification of network topology, it is difficult to analyze the influence of DFIG location on stability.

To overcome the defects of existing research, this paper proposes a theoretical method to analyze the influence of DFIG on the transient stability of multi-machine system, whose superiority mainly include the following aspects: Firstly, this approach proceeds from practical multi-machine power system, and the influence of DFIG on the system power angle stability is quantified. Secondly, the relation between DFIG location and its transient power output characteristics with the system transient stability is revealed according to this method. Finally, this will provide a theoretical basis for the reasonable configuration schemes which consider the wind farm access position and low voltage ride through technology synthetically.

2. ROTOR MOTION OF MULTI-MACHINE SYSTEM

According to extended equal area criterion(EEAC), all synchronous generators in a multi-machine system can be divided into leading cluster S and residual cluster A. The system of two clusters can be further equivalent to a single-machine infinite bus system, and the rotor motion equation can be expressed as follows [8].

$$M_{\mathrm{SA}}\ddot{\delta}_{\mathrm{SA}} = P_{\mathrm{m.SA}} - P_{\mathrm{e.SA}} = P_{\mathrm{m.SA}} - P_{\mathrm{c}} - P_{\max}\sin(\delta_{\mathrm{SA}} - \gamma) \quad (1)$$

Where：

$$\delta_{\mathrm{SA}} = \delta_{\mathrm{S}} - \delta_{\mathrm{A}} \quad (2)$$

$$M_{\mathrm{SA}} = \frac{M_{\mathrm{S}}M_{\mathrm{A}}}{M_{\mathrm{S}} + M_{\mathrm{A}}} \quad (3)$$

$$P_{\mathrm{m.SA}} = \frac{M_{\mathrm{A}}P_{\mathrm{m.S}} - M_{s}P_{\mathrm{m.A}}}{M_{\mathrm{S}} + M_{\mathrm{A}}} \quad (4)$$

$$\begin{cases} P_{\mathrm{c}} = \dfrac{M_{\mathrm{A}}\sum\limits_{i\in \mathrm{S}}\sum\limits_{k\in S}E_iE_kG_{ik} - M_s\sum\limits_{j\in \mathrm{A}}\sum\limits_{l\in \mathrm{A}}E_jE_lG_{jl}}{M_S + M_A} \\ P_{\max} = \sqrt{C^2 + D^2} \\ C = \dfrac{M_{\mathrm{A}} - M_{\mathrm{S}}}{M_{\mathrm{S}} + M_{\mathrm{A}}}\sum\limits_{i\in \mathrm{S}}\sum\limits_{j\in \mathrm{A}}E_iE_jG_{ij} \\ D = \sum\limits_{i\in \mathrm{S}}\sum\limits_{j\in \mathrm{A}}E_iE_jB_{ij} \\ \gamma = -\arctan\dfrac{C}{D} \end{cases} \quad (5)$$

3. QUANTITATIVE ANALYSIS OF THE INFLUENCE OF DFIG CONNECTION ON ELECTRICAL DISTANCE BETWEEN SYNCHRONOUS GENERATORS

The synchronous generator adopts the classic two-order model. Consider the synchronous generator as an inner electric potential node, thus all the nodes in the system can be divided into four categories: Inner electric potential nodes of generators in group A, inner electric potential nodes of generators in group S, outlet node W of DFIG and remaining power switching nodes R. According to the classification, the nodal voltage equations of the system are listed as:

$$\begin{bmatrix} \boldsymbol{Y}_{\mathrm{SS}} & \boldsymbol{Y}_{\mathrm{SA}} & \boldsymbol{Y}_{\mathrm{SW}} & \boldsymbol{Y}_{\mathrm{SR}} \\ \boldsymbol{Y}_{\mathrm{AS}} & \boldsymbol{Y}_{\mathrm{AA}} & \boldsymbol{Y}_{\mathrm{AW}} & \boldsymbol{Y}_{\mathrm{AR}} \\ \boldsymbol{Y}_{\mathrm{WS}} & \boldsymbol{Y}_{\mathrm{WA}} & \boldsymbol{Y}_{\mathrm{WW\_0}} & \boldsymbol{Y}_{\mathrm{WR}} \\ \boldsymbol{Y}_{\mathrm{RS}} & \boldsymbol{Y}_{\mathrm{RA}} & \boldsymbol{Y}_{\mathrm{RW}} & \boldsymbol{Y}_{\mathrm{RR}} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{E}}_{\mathrm{S}} \\ \dot{\boldsymbol{E}}_{\mathrm{A}} \\ \dot{\boldsymbol{U}}_{\mathrm{W}} \\ \dot{\boldsymbol{U}}_{\mathrm{R}} \end{bmatrix} = \begin{bmatrix} \dot{\boldsymbol{I}}_{\mathrm{S}} \\ \dot{\boldsymbol{I}}_{\mathrm{A}} \\ \dot{\boldsymbol{I}}_{\mathrm{W}} \\ \boldsymbol{0} \end{bmatrix} \quad (6)$$

Where $\boldsymbol{Y}_{\mathrm{WW\_0}} = G_0 + \mathrm{j}B_0$, which is the self-admittance of node W, $\boldsymbol{Y}_{\mathrm{SW}}$, $\boldsymbol{Y}_{\mathrm{AW}}$, $\boldsymbol{Y}_{\mathrm{RW}}$ are the mutual admittances between node W and the others. Obviously, the location information of DFIG has been included in the mutual admittance relationship between node W and other nodes of the system.

It's difficult to calculate the change of system power flow directly. Thus this paper use equivalent grounding conductance and susceptance model to express the external power characteristics of DFIG. By contracting node voltage equations twice, the location information of DFIG and power characteristics included in the equivalent grounding admittance are melted into the new admittance matrix [9]:

$$\begin{bmatrix} \boldsymbol{Y}''_{\mathrm{SS}} & \boldsymbol{Y}''_{\mathrm{SA}} \\ \boldsymbol{Y}''_{\mathrm{AS}} & \boldsymbol{Y}''_{\mathrm{AA}} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{E}}_{\mathrm{S}} \\ \dot{\boldsymbol{E}}_{\mathrm{A}} \end{bmatrix} = \boldsymbol{Y}''_{\mathrm{S\_A}} \begin{bmatrix} \dot{\boldsymbol{E}}_{\mathrm{S}} \\ \dot{\boldsymbol{E}}_{\mathrm{A}} \end{bmatrix} = \begin{bmatrix} \dot{\boldsymbol{I}}_{\mathrm{S}} \\ \dot{\boldsymbol{I}}_{\mathrm{A}} \end{bmatrix} \quad (7)$$

Where:

$$\begin{aligned} \boldsymbol{Y}''_{\mathrm{S\_A}} &= \begin{bmatrix} \boldsymbol{Y}'_{\mathrm{SS}} & \boldsymbol{Y}'_{\mathrm{SA}} \\ \boldsymbol{Y}'_{\mathrm{AS}} & \boldsymbol{Y}'_{\mathrm{AA}} \end{bmatrix} - \begin{bmatrix} \boldsymbol{Y}'_{\mathrm{SW}}\boldsymbol{Y}'^{-1}_{\mathrm{WW}}\boldsymbol{Y}'_{\mathrm{WS}} & \boldsymbol{Y}'_{\mathrm{SW}}\boldsymbol{Y}'^{-1}_{\mathrm{WW}}\boldsymbol{Y}'_{\mathrm{WA}} \\ \boldsymbol{Y}'_{\mathrm{AW}}\boldsymbol{Y}'^{-1}_{\mathrm{WW}}\boldsymbol{Y}'_{\mathrm{WS}} & \boldsymbol{Y}'_{\mathrm{AW}}\boldsymbol{Y}'^{-1}_{\mathrm{WW}}\boldsymbol{Y}'_{\mathrm{WA}} \end{bmatrix} \\ &= \begin{bmatrix} \boldsymbol{Y}'_{\mathrm{SS}} & \boldsymbol{Y}'_{\mathrm{SA}} \\ \boldsymbol{Y}'_{\mathrm{AS}} & \boldsymbol{Y}'_{\mathrm{AA}} \end{bmatrix} - \Delta\boldsymbol{Y} \end{aligned} \quad (8)$$

Define $\Delta\boldsymbol{Y} = \left[\Delta\boldsymbol{G}_{ij} + \mathrm{j}\Delta\boldsymbol{B}_{ij}\right]_{n\times n}$ as the modified matrix of the admittance matrix of the system.

4. THE INFLUENCE OF DFIG ACCESS LOCATION ON THE TRANSIENT STABILITY OF MULTI-MACHINE SYSTEM

The influence of DFIG connection on the transient stability of multi-machine system can be further analyzed by EEAC. Substituting the admittance correction value $\Delta \boldsymbol{Y}$ into (5), the variation of electromagnetic power of equivalent system is obtained:

$$\begin{aligned}\Delta P_{\mathrm{e}} = & \frac{M_{\mathrm{A}}}{M_{\mathrm{T}}}\sum_{i\in \mathrm{S}}\sum_{k\in \mathrm{S}} E_i E_k \Delta G_{ik} - \frac{M_{\mathrm{S}}}{M_{\mathrm{T}}}\sum_{j\in A}\sum_{l\in A} E_j E_l \Delta G_{jl} \\ & + \frac{M_{\mathrm{A}}}{M_{\mathrm{T}}}\sum_{i\in \mathrm{S}}\sum_{l\in \mathrm{A}} E_i E_l (\Delta B_{il}\sin\delta_{\mathrm{SA}} + \Delta G_{il}\cos\delta_{\mathrm{SA}}) \\ & + \frac{M_{\mathrm{S}}}{M_{\mathrm{T}}}\sum_{k\in \mathrm{S}}\sum_{j\in \mathrm{A}} E_j E_k (\Delta B_{jk}\sin\delta_{\mathrm{SA}} - \Delta G_{jk}\cos\delta_{\mathrm{SA}})\end{aligned} \tag{9}$$

Rotor motion equations of systems with DFIG can be obtained by modifying (1) with (9):

$$M_{\mathrm{SA}}\ddot{\delta}_{\mathrm{SA}} = \left(P_{\mathrm{m.SA}} - P_{\mathrm{c}} - \Delta P_{\mathrm{e}}\right) - P_{\max}\sin\left(\delta_{\mathrm{SA}} - \gamma\right) \tag{10}$$

As it can be known from the power angle characteristic of the system, the change of system equivalent mechanical power leads to the change of acceleration area and deceleration area, which has an impact on the transient stability of the system. During the first swing after the fault, when ΔP_{e}>0, DFIG benefits the transient stability of the system. Otherwise when ΔP_{e} <0, DFIG has a negative effect on the transient stability of the system.

Therefore, the connection of DFIG leads to the change of electrical distances between synchronous generators, the change of electromagnetic power of synchronous generators and equivalent mechanical power of system is calculated as well, finally the quantitative analysis of the transient stability of the multi-machine system with wind farm is realized.

4.1 Influencing factors of equivalent mechanical power of multi-machine system

The information of DFIG's access position is contained in the mutual admittance relation between node W and other synchronous generator nodes in the system. On the other hand, the power characteristics of DFIG with different LVRT schemes are different, which result in different effects on the electromechanical characteristics of generators. In this paper, the relation between these two factors and the equivalent mechanical power change of the system is deduced theoretically.

Assume that the synchronous generator has sufficient excitation capability, and take the inner electric potential of generators as per-unit value $\dot{E}_i = 1$ (i=1, 2,… ,n). Suppose there are p generators in the cluster S, and n-p generators in the cluster A. Considering the symmetry of node admittance matrix, rewriting (9) as matrix form:

$$\begin{aligned}\Delta P_{\mathrm{e}} = & \mathrm{Re}(\boldsymbol{Y}_{\mathrm{WW}}'^{-1})\cdot[\frac{M_{\mathrm{A}}}{M_{\mathrm{T}}}\mathrm{Re}(y_1) - \frac{M_{\mathrm{S}}}{M_{\mathrm{T}}}\mathrm{Re}(y_2) \\ & + \frac{M_{\mathrm{A}} - M_{\mathrm{S}}}{M_{\mathrm{T}}}\mathrm{Re}(y_3)\cos\delta_{\mathrm{SA}} + \mathrm{Im}(y_4)\sin\delta_{\mathrm{SA}}] \\ & + \mathrm{Im}(\boldsymbol{Y}_{\mathrm{WW}}'^{-1})\cdot[-\frac{M_{\mathrm{A}}}{M_{\mathrm{T}}}\mathrm{Im}(y_1) + \frac{M_{\mathrm{S}}}{M_{\mathrm{T}}}\mathrm{Im}(y_2) \\ & - \frac{M_{\mathrm{A}} - M_{\mathrm{S}}}{M_{\mathrm{T}}}\mathrm{Im}(y_3)\cos\delta_{\mathrm{SA}} + \mathrm{Re}(y_4)\sin\delta_{\mathrm{SA}}] \\ = & \mathrm{Re}(\boldsymbol{Y}_{\mathrm{WW}}'^{-1})\cdot X + \mathrm{Im}(\boldsymbol{Y}_{\mathrm{WW}}'^{-1})\cdot Y\end{aligned} \tag{11}$$

Where:

$$\begin{cases} y_1 = \sum_{i=1}^{p}\sum_{j=1}^{p}[-\boldsymbol{Y}_{\mathrm{SW}}'\boldsymbol{Y}_{WS}']_{(i,j)},\ y_2 = \sum_{i=1}^{n-p}\sum_{j=1}^{n-p}[-\boldsymbol{Y}_{\mathrm{AW}}'\boldsymbol{Y}_{\mathrm{WA}}']_{(i,j)} \\ y_3 = \sum_{i=1}^{p}\sum_{j=1}^{n-p}[-\boldsymbol{Y}_{\mathrm{SW}}'\boldsymbol{Y}_{\mathrm{WA}}']_{(i,j)},\ y_4 = \sum_{i=1}^{n-p}\sum_{j=1}^{p}[-\boldsymbol{Y}_{\mathrm{AW}}'\boldsymbol{Y}_{\mathrm{WS}}']_{(i,j)} \end{cases} \tag{12}$$

The expression (11) shows: X and Y are the linear combinations of electrical distance between node W and other nodes, and are related to network topology, which mainly involve the influence factor of DFIG location. $\mathrm{Re}(\boldsymbol{Y}_{\mathrm{WW}}'^{-1})$ and $\mathrm{Im}(\boldsymbol{Y}_{\mathrm{WW}}'^{-1})$ are only related to the equivalent ground admittance of DFIG, which indicates the external power characteristic expressed by y_{dfig} .Therefore, (11) shows the mathematical relation between the mechanical power variation of equivalent system with the location information and the power characteristics of DFIG.

4.2 The influence regularity of DFIG access location on the transient stability of multi-machine system

As the network structure of power system is determined and the DFIG equivalent ground admittance model is introduced, the self-admittance of node W becomes:

$$\boldsymbol{Y}_{\mathrm{WW}}' = \boldsymbol{Y}_{\mathrm{WW\_0}}' + y_{\mathrm{dfig}} = (G_0 - g_{\mathrm{dfig}}) + \mathrm{j}(B_0 + b_{\mathrm{dfig}}) \tag{13}$$

Due to the capacity limitation of the DFIG converter, the reactive power output of DFIG control system is limited, thus the value of $B_0 + b_{\mathrm{dfig}}$ is positive. In addition, the reactance of the electric elements is usually much larger than the resistance, i.e. $\left|B_0 + b_{\mathrm{dfig}}\right| \gg \left|G_0 - g_{\mathrm{dfig}}\right|$. According to (13), the variation of system's equivalent mechanical power can be rewritten as:

$$\Delta P_{\mathrm{e}} = \frac{G_0 - g_{\mathrm{dfig}}}{(B_0 + b_{\mathrm{dfig}})^2}X - \frac{1}{B_0 + b_{\mathrm{dfig}}}Y \tag{14}$$

The larger ΔP_{e} is, the better transient stability the system will have. Calculate the partial derivatives of F to g and b as follow:

$$\begin{cases} \dfrac{\partial \Delta P_e}{\partial g} = -\dfrac{X}{(B+b)^2} & \text{(a)} \\ \dfrac{\partial \Delta P_e}{\partial b} = \dfrac{1}{(B_0+b)^2}\left(Y - \dfrac{2(G_0-g)X}{(B_0+b)}\right) \approx \dfrac{Y}{(B_0+b)^2} & \text{(b)} \end{cases} \tag{15}$$

The following is a detailed discussion on the configuration regularity of the location and LVRT scheme of DFIG to benefit the transient stability of the system.

1) When X>0, $\frac{\partial \Delta P_e}{\partial g}$ is negative according to (15.a), which means reduces with the increase of g, so LVRT scheme which outputs less (or absorbs more) active power to the system should be adopted; while X<0, on the contrary, LVRT scheme which outputs more (or absorbs less) active power to the system should be adopted.

2) When Y>0, $\frac{\partial \Delta P_e}{\partial b}$ is positive according to (15.b), which means increases with the increase of g, so LVRT scheme which outputs mores (or absorbs less) reactive power to the system should be adopted; while Y<0, LVRT scheme which outputs less (or absorbs more) reactive power to the system should be adopted conversely.

Therefore, by calculating the values of X and Y and power characteristics of DFIG for different LVRT schemes, reasonable coordination of LVRT schemes and DFIG locations could be obtained, thus the transient stability of multi-machine system with DFIG is enhanced.

5. EXAMPLE ANALYSIS

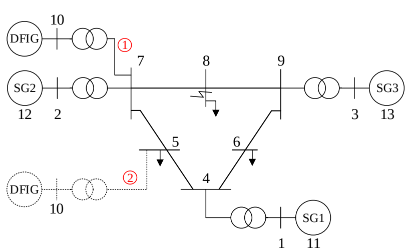


Fig 1 A three-machine system with DFIG

Fig 1 shows a three-machine system with DFIG. The rated capacity of synchronous generator SG1, SG2 and SG3 are respectively 247.5MW, 192MW and 128MW, and the rated power output of DFIG is 90MW. The three-phase fault occurs at node 8, which lasts from 0.2s to 0.5s. All the loads are concerned as constant impedances. In this case, SG2 and SG3 belong to the leading cluster S, and SG1 belongs to the remaining cluster A. Simulation results of two LVRT schemes under different cases are compared: DFIG is connected to node 7 near cluster S or connected to node 5 near cluster A. The two LVRT schemes are:

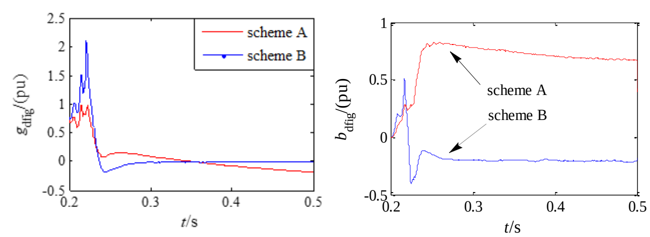
Scheme A: Stator series reactance scheme [10]. The inductance value is set to be 0.153 p.u..

Scheme B: Rotor side crowbar scheme [11]. The resistance of crowbar is set to be 0.1Ω.

The series reactance will be activated at the moment DFIG detecting the dip of grid voltage, and will be deactivated as soon as the fault is eliminated.

5.1 Power characteristics of DFIG under different LVRT schemes

Fig 2 shows the compared results of scheme A and B on equivalent conductance and susceptance respectively in the case of DFIG is connected to node 7. It can be seen that conductance is positive in both cases, which means DFIG absorbs active power from the system. In addition, DFIG equipped with scheme A is able to control the RSC during the fault time, so that it can provide reactive power support to the system during the fault, which corresponds to its positive susceptance. As scheme B shuts down the RSC when crowbar is activated, the susceptance under scheme B is negative.



(a) conductance (b) susceptance

Fig 2 Comparison of the equivalent conductance and susceptance of DFIG during fault

5.2 The influence of DFIG access location on transient power angle stability of system

(1) DFIG is connected to node 7

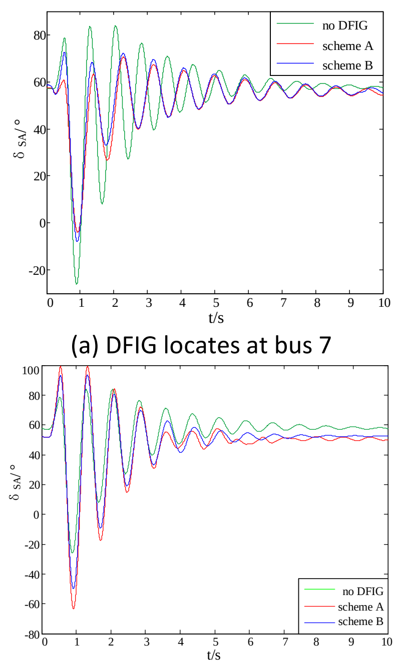
When DFIG is connected to node 7, the average values of X and Y that indicate the DFIG location are: $\bar{X}_7 = 1.151 > 0$, $\bar{Y}_7 = 0.226 > 0$ .The variation of equivalent mechanical power of system caused by DFIG under the two LVRT schemes are: $\Delta P_{e.A} = 0.0401$, $\Delta P_{e.B} = 0.0349$.

Fig 3 (a) shows the variation of equivalent power angle in three cases. As it can be seen from the simulation results, when scheme A is adopted, the maximum value of the equivalent power angle curve is smaller than that under scheme B, which indicates that system receives less accelerating energy. Besides, the maximum values of equivalent power angles under both schemes are smaller than the case of system without DFIG. Therefore, compared with scheme B, scheme A is more beneficial to the system transient stability, which verity the correctness of the theoretical analysis.

(2) DFIG is connected to node 5

While DFIG is connected to node 5, the average value of X and Y are: $\bar{X}_5 = -13.518 < 0$, $\bar{Y}_5 = -0.716 < 0$. The variations of equivalent mechanical power in per-unit value under two LVRT schemes are: $\Delta P_{\mathrm{e.A}} = -0.3119$, $\Delta P_{\mathrm{e.B}} = -0.2743$.

Fig 3 (b) shows the simulation results in the case of DFIG connected to node 5. It can be seen that the max amplitude of equivalent power angles of system with DFIG under both LVRT schemes are larger than that of system without DFIG. That validates the inference that this DFIG location is detrimental to transient stability. Besides, the first swing of equivalent power angle under scheme A is larger compared with scheme B, which indicates that scheme A is more detrimental to transient stability. The simulation results verify the correctness of the theoretical analysis.



(b) DFIG locates at bus 5

Fig 3 Equivalent power angle of three-machine system

6. CONCLUSION

(1) By means of contracting node admittance matrix of system, the influence of DFIG on the system power angle stability is transformed into the change of self and mutual admittance of synchronous generator nodes, thus the quantitative analysis is realized.

(2) The regularity about the location and LVRT scheme of wind farm to improve the transient stability of multi-machine system is derived, which provides a theoretical reference for reasonable configuration of wind farm.

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